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Heteroepitaxial InP Solar Cells on Si and GaAs Substrates

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SUMMARY

The characteristics of InP cells processed from thin layers of InP hetero-epitaxially grown on GaAs, on silicon with an intervening GaAs layer and on GaAs with intervening $Ga_xIn_{1-x}As$ layers are described and the factors affecting cell efficiency discussed. Under 10 MeV proton irradiations, the radiation resistances of the heteroepitaxial cells were superior to that of homoepitaxial InP cells. The superior radiation resistance is attributed to the high dislocation densities present in the heteroepitaxial cells.

INTRODUCTION

InP solar cells are prime candidates for use in the space radiation environment. This follows from their superior radiation resistance, annealibility and theoretically predicted air mass zero efficiencies of over 22 percent (ref. 1). To date, AMO, total area efficiencies over 19 percent are reproducibility achieved for cells 4 cm^2 in area, InP cells produced by the Nippon Mining Corporation are presently powering a small lunar orbiting satellite and a NASA Lewis InP solar cell module shows no degradation after 3 years in space (refs. 2 to 4). Despite these achievements, and others, the presently high InP substrate cost presents a roadblock to the widespread use of these cells in space. One solution to this problem lies in producing solar cells from thin layers of InP epitaxially grown on cheaper, more durable substrates (ref. 5). In the present case we describe the initial results emanating from our program aimed at processing solar cells from thin layers of InP using either Si or GaAs as the substrate material. Additional results emerging from a program, at the Solar Energy Research Institute (SERI), are included for completeness in describing major U.S. programs in this area.

CELL DETAILS

The research effort includes cells processed by OMCVD on silicon substrates with an intervening GaAs layer (InP/GaAs/Si), InP deposited directly on GaAs (InP/GaAs) and InP deposited on GaAs with intervening layers of $Ga_xIn_{1-x}As$ (InP/$Ga_xIn_{1-x}As$/GaAs). The InP/GaAs and InP/GaAs/Si cells were processed at the Spire Corporation in a NASA Lewis sponsored program, while the InP/Ga_xIn_{1-x}As/GaAs cells were produced by the Solar Energy Research Institute (refs. 6 and 7). Pertinent cell details are shown in figure 1, while performance parameters of the best cells in each category are shown in table I.

FACTORS AFFECTING CELL PERFORMANCE

As initially shown by Yamaguchi et al. (ref. 5), high dislocation densities have a drastic effect on the performance of heteroepitaxially grown InP

solar cells. Lattice mismatch is one major factor contributing to the high dislocation densities. This is qualitatively illustrated in table I, where the best performance is exhibited by the InP/$Ga_xIn_{1-x}As$/GaAs cell. This follows from the fact that the latter cell with x = 0.47 is lattice matched to InP while the mismatch between InP and GaAs is ~4 percent. Efficiencies approaching 20 percent are anticipated when the InP/$Ga_x In_{1-x}As$/GaAs cell is optimized. Dislocation densities have not been determined for this latter cell. On the other hand, it has been determined that dislocation densities for the remaining cell configurations range between 3×10^8 and 8×10^8 cm^{-2} (refs. 6 and 8). It is noted that a reduction in dislocation density of several orders of magnitude is required in order to reach efficiencies over 18 percent (ref. 5).

Results obtained from transmission electron microscopy indicate that the dislocation density is greatest at the semiconductor interfaces and decreases markedly as one progresses toward the cell junction (refs. 6 and 8). As seen in table II, the values obtained for J_{01} and J_{02}, the diffusion and recombination components of the cell's dark current, respectively, are consistent with the observed dislocation density distribution in the heteroepitaxial cells. This follows from the observation that J_{01} and J_{02} are significantly greater for the heteroepitaxial cells when compared to the values obtained for these parameters in the homoepitaxial cell shown in table II. Furthermore the greatest such difference occurs in J_{01}, the diffusion component. Due to the dislocation density distribution, the recombination component, which is attributable to recombination in the depletion region is affected by a relatively low dislocation density while the diffusion component is predominantly due to dark current in the cell's high dislocation density base region.

It is believed that the reduced efficiency of the InP/GaAs/Si cell is due to a high series resistance. In fact it was found that the series resistance of the InP/GaAs/Si cell was 4.75 Ω-cm^2 compared to 0.8 Ω-cm^2 for InP/GaAs. The high series resistance of the InP/GaAs/Si cell originates from the necessity to short out a reverse diode formed, during processing, by diffusion of the n-dopant Si into the GaAs. This is accomplished by shorting out the GaAs buffer layer in regions outside the cell's active area thus creating a high resistance path to the cell's back contact (ref. 6).

PROTON IRRADIATIONS

To date, no InP/$Ga_xIn_{1-x}As$/GaAs cells were available for exposure to radiation. However, the remaining cells were irradiated by 10 MeV protons to a fluence slightly in excess of 10^{13} cm^{-2}. The results, in terms of cell maximum power, are shown in figure 2. The excellent radiation resistance of these cells is further illustrated by a comparison of the InP/GaAs cell with a homoepitaxial n^+p InP cell (fig. 3). A similar result applies to the remaining cell parameters (ref. 9).

Carrier removal was determined from plots of $1/C^2$ versus V both before and after irradiation. It was found that, after irradiation to a fluence of 1.1×10^{13} cm^{-2}, the cells p-base carrier concentration decreased from a pre-irradiation value of 3×10^{16} to 1×10^{16} cm^{-3} hence the carrier removal rate is 1.8×10^3 cm^{-1}. In comparison, the carrier removal rate for 1 MeV electrons is 2.2 cm^{-1} (ref. 10). It should be noted that the latter value was obtained for

a homoepitaxial n^+p InP cell (ref. 10). Aside from cell differences, considering the much higher energy and the tendency of protons to form defect clusters, one expects relatively higher values for the present proton irradiations. However, aside from these differences, the basic mechanism of carrier removal is uncertain in both cases.

The effect of carrier removal on series resistance was determined using:

$$\Delta R_s = \frac{L}{Aq} \left[\left(\frac{1}{p\mu_p} \right)_\phi - \left(\frac{1}{p\mu_p} \right)_o \right]$$

where L is the cell's p-base width, A is the cell area, and the subscripts o and ϕ denote pre- and post-irradiation values, respectively. Using L = 3 μm, A = 0.25 cm^2, and 150 and 170 cm^2 V^{-1} sec^{-1} for the pre- and post-irradiation mobilities, respectively, one finds that ΔR_s = 0.004 Ω. Therefore carrier removal has a negligible effect on cell series resistance.

CONCLUSION

Although the radiation resistances of the InP/GaAs and InP/GaAs/Si cells are significantly greater than those observed for homoepitaxial InP cells, the present results are not intrinsic to InP. In the present case, the high dislocation densities lead to extremely short pre-irradiation diffusion lengths. Hence, dislocations dominate in both the pre- and post-irradiation cell performance. Aside from the obvious need to reduce dislocation densities by several orders of magnitude, it is most desirable to process the cells using silicon substrates. In this case, in addition to considerable reduction in cost, the greater mechanical strength of Si facilitates chemical thinning of the resultant cell. Unfortunately Si is an n-dopant in InP and GaAs. Hence, during the processing, diffusion of Si into the p-type buffer layer forms a reverse diode which drastically degrades cell performance. This problem requires solution before high efficiency heteroepitaxial InP cells can be formed using Si substrates. Use of the p^+n InP cell configuration is one solution to this problem. This, and other possible solutions, appear to be more workable than the quick fix obtained by shorting out the GaAs layer in the InP/GaAs/Si cell. This procedure, although resulting in increased efficiency, leads to a high cell series resistance. An additional problem although of a more basic and academic nature, lies in determining the basic mechanisms of carrier removal due to both proton and electron irradiations.

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TABLE I. – CELL PERFORMANCE PARAMETERS

Cell	Efficiency, percent	Voc, mV	Jsc, mA/cm^2	FF, percent
InP/GaInAs/GaAs	13.7	783	31.7	75.7
InP/GaAs	10.8	705	28.9	72.7
InP/GaAs/Si	7.1	644	26	58.2

TABLE II. – DIFFUSION AND RECOMBINATION PARAMETERS

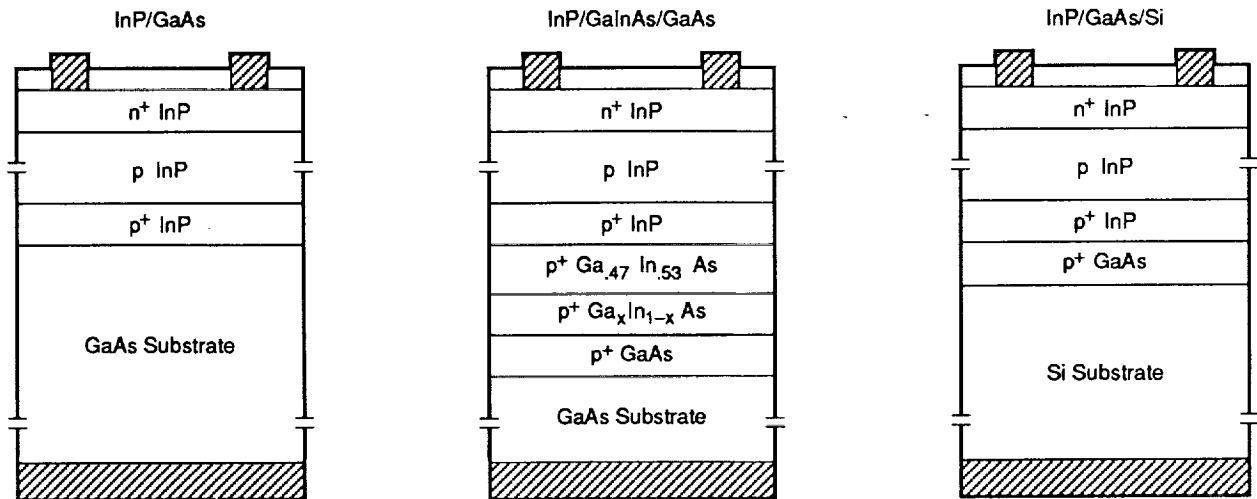| Cell	A_1	A_2	J_{01}, A/cm^2	J_{02}, A/cm^2
InP	1.03	2.24	1.4×10^{-16}	4.1×10^{-9}
InP/GaAs	1.27	2.12	6.6×10^{-11}	1.0×10^{-7}
InP/GaAs/Si	1.26	2.15	1.7×10^{-10}	1.5×10^{-7}

Figure 1.—Heteroepitaxial InP cell details.
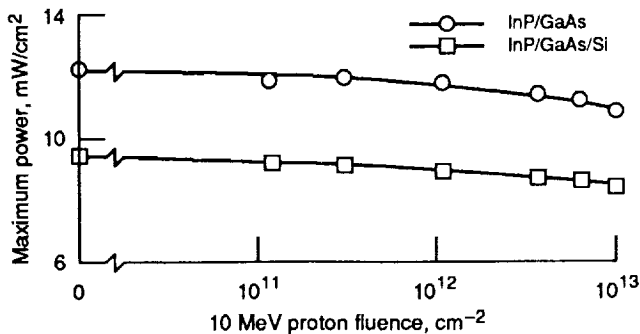

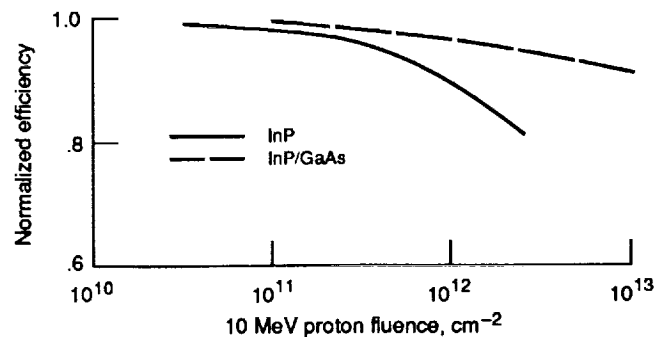
Figure 2.—Cell maximum power versus 10 MeV proton fluence.

Figure 3.—Normalized efficiencies after proton irradiation.

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16. Abstract

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